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PROGRESS REPORT ON THE USE OF WOOD WASTE FOR ACID MINE-WATER POLLUTION-ABATEMENT

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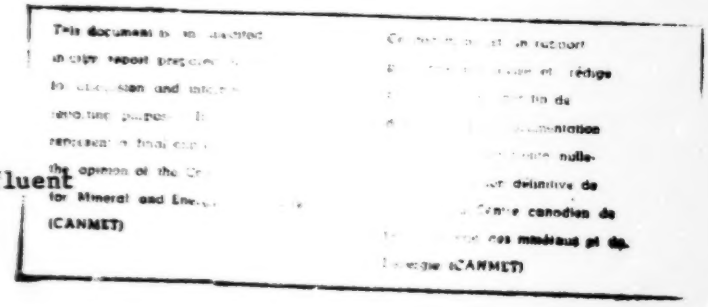
August 1983



Project MRP-3.5.0.1.01
Control of Uranium Tailings Effluent

MINERALS RESEARCH PROGRAM
MINERAL SCIENCES LABORATORIES
DIVISION REPORT MRP/MSL 83-116 (IR)

49 pp

NOV 22 1984
MICROMEDIA

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by

A. Jongejan

ABSTRACT

The feasibility of using a microbial wood-cellulose degradation, sulphate-reduction process for practical acid mine-water pollution-abatement was investigated. A laboratory process-simulation showed a significant purification of Elliot Lake tailings effluent, decreasing the U, Th and Ra contents below detectable levels. ph-values below 3.5, iron-hydroxide precipitation on, and excessive aeration of the wood waste allowing the development of abundant fungal growth, retarded the process. The pH-increase from 3.5 above 5, required to activate sulphate-reducing micro-organisms for precipitating heavy metals as sulphides, occurred in less than four hours. This depended more on the wood-waste length through which the water flowed, than on the wood volume. Optimization of the composition of the microbial population is primarily connected with process maintenance rather than the pH-increase rate. Although the preferable flow rate over a 2.4-m wood-waste length was 0.45 $mL/min/cm^2$, slower flow rates are required for waters of pH-values lower than 5. The possible abatement capacity of wood waste was estimated. An effluent volume from yearly precipitation on 100-200 acres of tailings (similar in sulphide - carbonate ratio of Elliot Lake tailings) might be treated by wood waste in one or two 50-m long ditches.

The determination of the effect of flushing instead of the weekly recirculation used in the experiments could not be done in the laboratory because of limited space. The extension of the experiments may be done more economically in the field where size reduction can be minimized to allow for the actual wood waste grain sizes that cannot be reduced. Although favourable results for a practical process application were obtained, the same must still be acquired on this aspect before lengthy work on process optimization is justified. Suggestions for field- and further laboratory experimentation are included.

RAPPORT PROVISOIRE SUR L'UTILISATION DES DÉCHETS DE BOIS POUR DIMINUER LA POLLUTION DES EAUX ACIDES D'EXHAURE

par

A. Jongejan

RÉSUMÉ

Les recherches ont porté sur l'utilisation possible d'un processus microbien de dégradation de la cellulose et de réduction du sulfate pour diminuer la pollution des eaux acides d'exhaure. Une simulation en laboratoire a permi de constater qu'une épuration importante des effluents de la mine d'Elliot Lake s'était produite abaissant la teneur en U, Th et Ra à des niveaux imperceptibles. Des valeurs pH inférieures à 3,5, la formation d'un précipité d'hydroxide de fer ainsi que l'aération excessive des déchets de bois ayant favorisé la croissance abondante de champignons ont ralenti le processus. L'augmentation de la valeur pH de 3,5 à 5 requise pour activer les micro-organismes qui réduisent le sulphate dans la précipitation de métaux lourds tels les sulfures, s'est produite en moins de quatre heures en raison surtout de la longueur des déchets de bois où l'eau s'écoulait plutôt que du volume du bois. L'optimisation de la composition de la flore microbienne est davantage liée à la maintenance du processus qu'au taux d'augmentation du pH. Bien que le taux désirable du débit sur une étendue de déchets de bois de 2,4 m soit de 0,45 mL/min/cm^2, des taux de débit plus lents sont requis pour les eaux qui ont un pH inférieur à 5. On a fait l'appréciation de la capacité d'élimination des déchets de bois. Le volume des effluents provenant des précipitations annuelles sur une superficie de 100 à 200 acres de résidus (le rapport sulphite-carbonate est semblable dans le cas des résidus d'Elliot Lake) pourrait être traité à l'aide de déchets de bois empilés dans un ou deux fossés de 50 m.

En raison de l'exiguité des locaux, il serait impossible de déterminer en laboratoire si un lavage serait préférable à la recirculation hebdoma-

daire utilisée au cours des essais. Il serait possible de prolonger les expériences de façon plus rentable sur le terrain où les déchets peuvent être réduits au minimum de façon à inclure des déchets dont la dimension des grains empêche la réduction. Bien que les essais aient donné des résultats favorisant l'application pratique de cette méthode, il sera nécessaire d'obtenir des résultats concluants lors d'essais menés sur le terrain pour justifier la nécessité d'entreprendre un long travail sur l'optimisation du processus. Ce rapport présente des suggestions portant sur les essais futurs en laboratoire et sur le terrain.

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INTRODUCTION

The interaction between wood-degrading and sulphate-reducing micro-organisms has been studied in connection with pollution-abatement of acid mine-water. Tuttle et al. (1,2) reported that the acidity and sulphate content of an acid mine-water stream in Ohio were substantially reduced following seepage through a dam of decaying wood waste. Sulphate-reducing organisms in the water downstream from the dam, utilizing cellulose-degradation products as a carbon source, precipitated heavy metals as sulphides. An experiment to verify that no unknown local conditions were required for the interaction between the microbial species has been described previously (3). The scale of that experiment was presently enlarged to obtain information for the practical application of the process.

The beginning and end of a practical process abating water-pollution from small acid mine-water streams or abandoned sulphide-tailings areas could be visualized. For instance, a dam could be constructed to control and guide polluted water into a ditch. In this ditch the water would be treated with decaying wood waste. The effluent could be collected in a series of settling lagoons where the metal sulphides would precipitate and could be recovered. Overflow from the settling lagoons would follow the natural drainage creek bed when the sulphide content would be sufficiently low. The problem in applying the natural process was, therefore, the water treatment with decaying wood waste.

Experiments to determine the principles of the microbial process in the wood waste (cellulose) have been described elsewhere (4). The results suggested that the conditions in the wood waste should be only partially oxidative. Furthermore, the possibility of developing a layered structure of the microbial population in the wood should not be prevented by water turbulence which is produced by aeration methods applied directly to a wood-waste water mixture. These requirements concerned the design of the waterflow through the wood waste. The experiments (4) had not included the lengthy determinations of the composition of the microbial population that would produce optimum abatement conditions. Only promising results of the flow-design experiments for a practical application of the process would justify experiments on the relevant microbial ecology in the wood and settling lagoons to improve the abating rate.

The experiments described in this report therefore, deal with the design of the waterflow in the ditch. The waterflow from acid tailings, through wood waste into a settling lagoon, was simulated in a laboratory arrangement using troughs filled with wood waste. Observations made on this simulation can be used for further field tests. This simulation was compared with another laboratory test using twice the length but the same cross-section of the wood waste in the troughs. Information was obtained about the effects of water flowrate variations on the pH to evaluate practical process applicability and to arrive at a conservative estimate of the abating capacity. Although the microbial process decreases water acidity and removes heavy metals by sulphide precipitation, sorption of heavy metals by wood independent of micro-organisms can be expected to take place also (5,6). Because of the particular experimental arrangement, these processes could not be considered separately.

Polluted acid-water treatment with wood waste, generally, should be considered a process to be applied to small ditches or creeks because of the limited capacity of the method. A treatment of the polluting source, such as abandonned tailings areas themselves, remains the principal method for abating pollution.

MATERIALS AND METHODS

MATERIALS

Softwood waste from a sawmill having particle sizes; +5.6 mm 10%; -5.6 mm + 4 mm 11%; -4 mm + 1.4 mm 47% and -1.4 mm 32% was mixed with paper-cardboard waste (-2 mm) in a weight ratio 6:1. The wood waste was obtained from a pile exposed to the weather. Therefore, the extent of degradation of the wood was unknown.

Acid-decreasing and cellulose-degrading bacterial species described previously (4), Aeromonas, Pseudomonas (I)(II), Achromobacter, Flavobacter, Bacillus, "Cellulomonas" (I)(II), Microcyclus and Micromonospora as well as the wood-degrading fungi Polyporus versicolor, Lenzites trabea and Trichoderma viride were used in the experiments. The effluent from lysimeter experiments on Elliot Lake tailings was used as a source of polluted water (7).

APPARATUS

a. The arrangement simulating an acid mine-water source, a ditch with wood-waste mix and settling lagoons is shown in Figure 1. It consistsof a 25-L polyethylene bottle (A), two 3/8-inch thick polycarbonate troughs* (B) positioned at 24° and two 70-L polyethylene tanks (C).

The flowrate from bottle (A) was regulated with the stopcock outlet or the input from a Model-7017-21 Masterflex (variable drive) pump (see "Recirculation", Fig. 1). The water from the troughs containing the wood-waste mix was fed to the bottom of one tank (C_1). The water from the top of this tank was recirculated or transferred by siphon to the bottom of the second tank (C_2). Overflow from tank (C_2) was recycled, discarded, or collected periodically as samples of "purified water". The construction of the troughs is shown in Figure 2. The slope at which the troughs were positioned could be varied. Aeration in the troughs was achieved by placing air-dispersion tubes in the spaces between the plates of each baffle unit. Gravel (coarse quartz) was piled against the baffle windows (2.5 cm high x 10 cm wide) to allow a fast water flowrate.

b. In another arrangement the wood-waste, cellulose mix was placed in three 1.2-m long, 60-mm diameter and one 70-mm diameter vertical glass-tubes closed at the bottom with a rubber stopper (Fig. 3). The cross-section of the tubes had approximately the same size as the screened windows in the bottom of the baffles of the troughs (Fig. 1). The polluted water seeped through the total column-length of approximately 4.8 m (twice the combined lengths of the troughs). Model-7017 Masterflex pump provided with four pump heads was used to bring the effluent from one column into the next. A 4-L beaker was placed under each of the three columns to receive the effluent through an outlet in the stopper. The fourth (70 mm) column was connected with a 70-L polyethylene tank similar to the trough arrangement.

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*Construction by J. Sanjuan, engineering technologist, Technical Services Division, CANMET, Energy, Mines and Resources Canada.

Partial aeration was accomplished by feeding air in the bottom of a 1/4-inch polyethylene tube of which the upper two-thirds was perforated and the top closed with a rubber stopper. This tube was placed inside each of the glass tubes by passing it through the rubber stopper at the bottom. The aeration tubes were surrounded with the wood-waste mix.

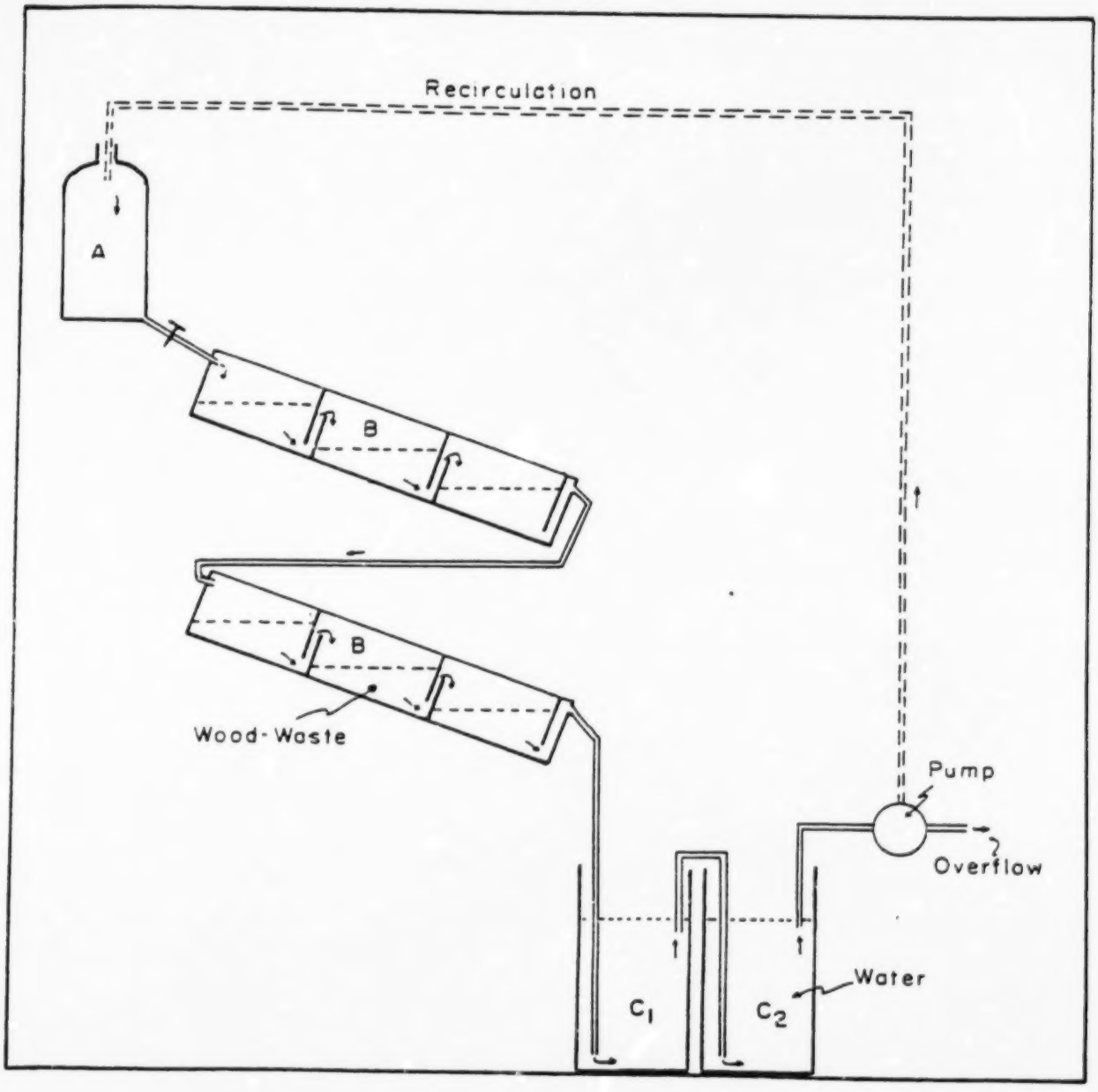

Figure 1. Simulation of an acid mine-water pollution-abatement system

A - Source of polluted water

B - Water treatment with degrading wood waste

C - Settling tanks for collecting heavy-metal sulphides

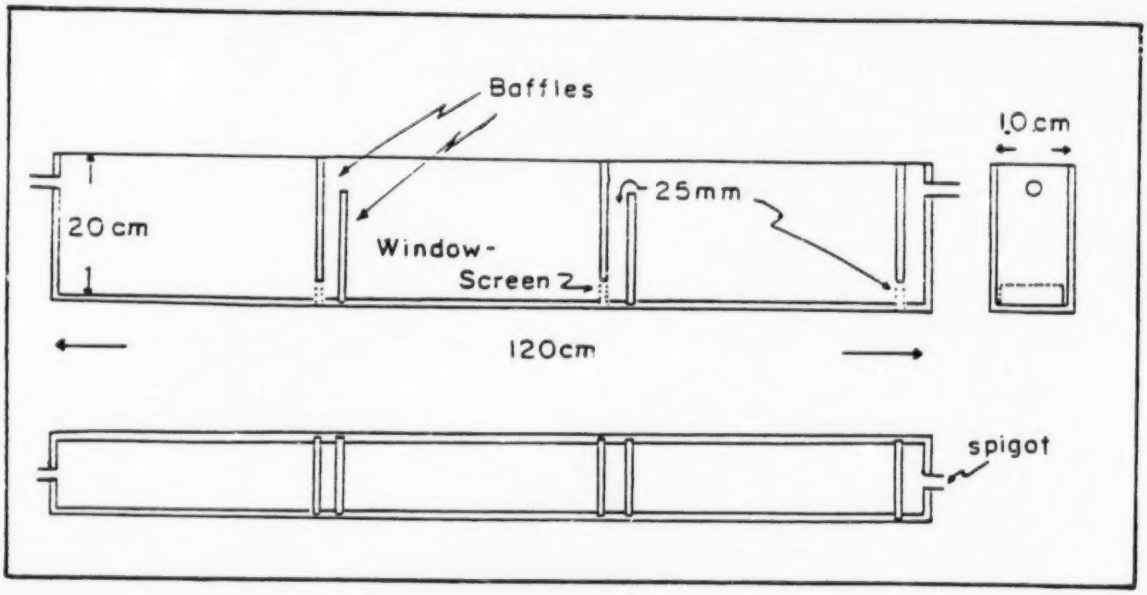

Figure 2. Trough ('B', Fig. 1) for water treatment with degrading wood waste

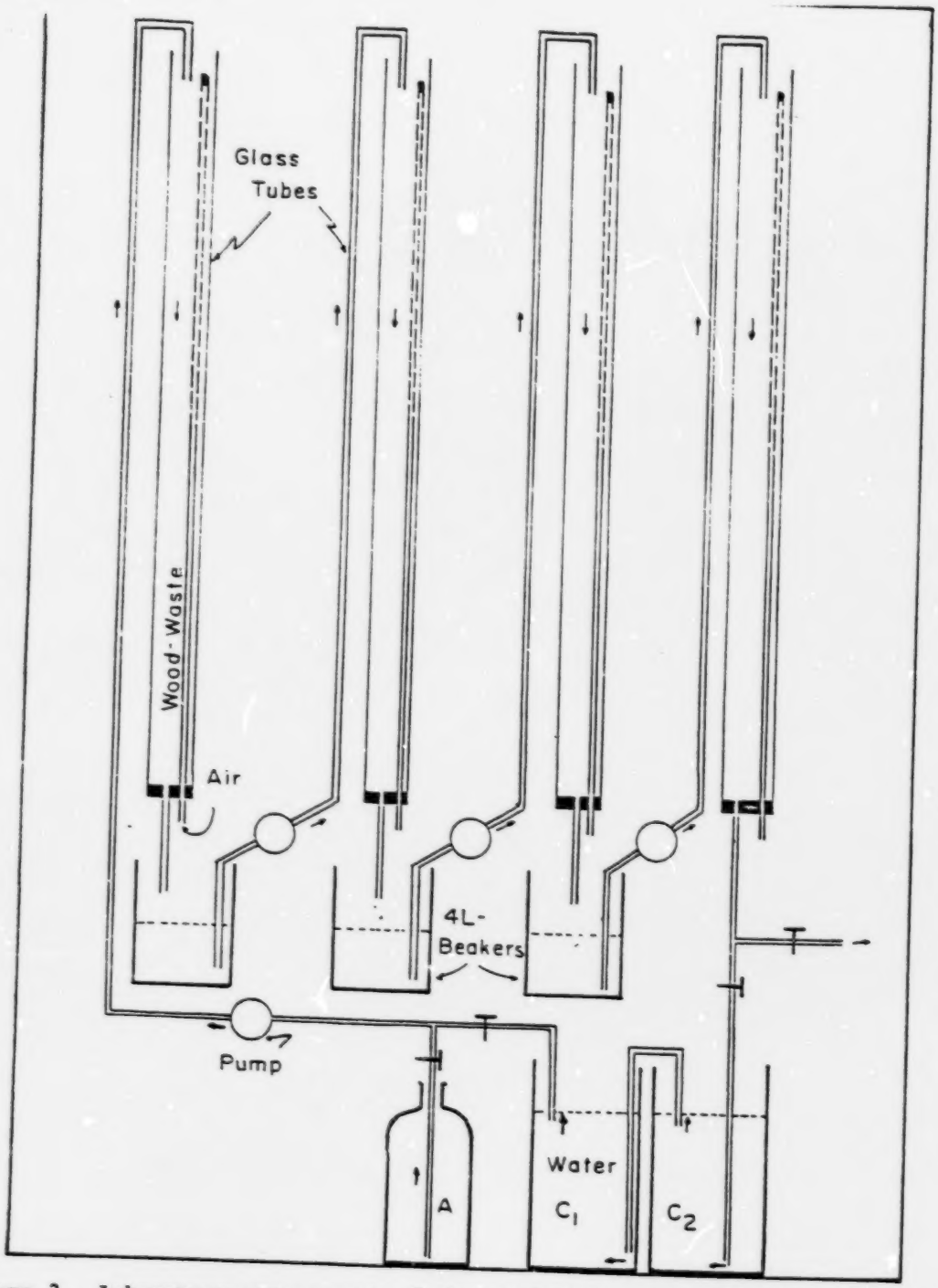

Figure 3. Laboratory arrangement of the acid mine-water pollution abatement system

A - Source of polluted water

C - Settling tanks for collecting heavy-meal sulphides

METHODS

a. Estimation of Maximum Flowrate in Wood Waste

The maximum flowrate was estimated by passing water through various lengths of wood-waste columns in 1.2 m long glass-tubes having different diameters (30-70 mm) and measuring the flowrates.

b. Effects of Flowrate Variations on pH-5 Solution

Six 300-mL cultures of pH-increasing bacteria, two 300-mL of cellulolytic bacteria and one 300-mL of fungal species were grown using a Model G-24, Environmental Shaker (New Brunswick Co.). The micro-organisms were grown for 10 days in nutrient-I containing 1% cellulose, 0.25% soluble starch, 0.15% trypticase-peptone (BBL), 0.1% phytone-peptone (BBL), 0.05% Yeast Extract, 0.005% $FeSO_4.7H_2O$ and 0.0025% $MnSO_4.H_2O$ in distilled water adjusted to pH 5.5 with 10% (v/v) HCl.

The troughs and tubes were filled each with respectively 1 kg (≈6.7 L) and 0.5 kg wood-waste mix that had been autoclaved at 120°C for 20 min and subsequently wetted with nutrient-IIa. This solution contained NH_4NO_3 0.1%, $MgSO_4.7H_2O$ 0.005%, $CaCl_2.2H_2O$ 0.001%, K_2HPO_4 0.01%, KH_2PO_4 0.003%, $FeSO_4.7H_2O$ 0.015%, $MnSO_4.H_2O$ 0.001% and Yeast Extract 0.05% in microfiltered (~0.2 μ) tap water, adjusted to pH 5 with 10% (v/v) HNO_3, after standing overnight. A 35-L volume was recirculated for one day after which the cultures were flushed in (instead of mixing them in the wood waste) so that the microbial population could develop a layered structure. The cultures were distributed through each system by recirculating the solution at approximately 25 mL/min for 6 days. A fresh solution was recirculated at approximately 50 mL/min (day 7-14) and at approximately 75 and 100 mL/min (day 15-18). After 18 days the recirculation was stopped for 2 days to determine the effect of stopping the waterflow. Waterflow was resumed for two days (day 21-22) at approximately 50 mL/min to simulate recovery from short stagnant conditions. The pH was monitored during the experiments.

c. Effects of High-Ferrous Iron on a pH-3.5 Solution

After 22 days the solution in each system was replaced by a similar solution-IIb containing additionally Na_2SO_4 0.1%, $FeCl_2.4H_2O$ 0.25% (instead of $FeSO_4.7H_2O$), $CaCl_2.2H_2O$ 0.005% and Yeast Extract 0.025% in tapwater. The pH of the solution had been adjusted to 3.5 with 10% (v/v) HNO_3 after

standing overnight. The composition included approximately twice the iron content (as ferrous iron) of Elliot Lake tailings effluent, and had a similar sulphate content. The replacement was done by feeding 45 L solution-IIb in each system at a flowrate of 25 mL/min and discarding the previously used solution in tanks (C) and 10 L effluent before recirculation. The total wood-waste volume in each system was approximately 14 L and its interstitial water content was determined at 65% so that a minimum of 9 L water in the troughs and tubes had to be discarded. The effects of the high-ferrous iron solution were monitored for 11 days (day 23-34).

d. Estimation of Maximum Flowrate for pH 3.5 Abatement and Effects of High Ferric Iron

Because the pH had dropped below 5 (the limit of sulphate-reducer activity) under the previous conditions and a thick iron-hydroxide coating covered the wood in the troughs, the mix was discarded. It was replaced in both arrangements with a fresh, sterilized, mix which was treated with the microbial cultures and nutrient-IIa for 9 days (day 35-44). The flowrate was increased 25 mL/min every 7 days, discarding the solutions in tanks (C) and 10 L effluent before recirculating a fresh pH-3.5 solution-IIa (days 44, 51, 58). Flowrates higher than 100 mL/min were not considered, being close to the maximum physical flowrate through the wood.

After reaching 100 mL/min (day 65) the flowrate was reduced to 65 mL/min and a fresh, non-sterilized, pH-3.5 solution-IIa with an addition of $Fe(NO_3)_3.9H_2O$ 0.17% and Na_2SO_4 0.07% was pumped in. This solution contained approximately half the iron content of Elliot Lake tailings effluent and a sulphate-equivalent slightly below the iron content. The iron, however, was present as a hydroxide precipitate, to a great extent. The use of the glass-tube arrangement in the experiments was discontinued because of inferior performance in decreasing the water acidity. The solution in tank (C) used in the glass-tube experiment was connected by siphon to that used with the troughs (day 72) as tank (C_2). Only one tank for each set-up had been used in the experiments. Observations on this arrangement (day 72) continued till day 100.

The dissolved oxygen content of the water was determined by Hach's modification of Winkler's method (8), and the total-iron and sulphate

contents were determined also using Hach's methods (8). The O_2-analyses were done to obtain information about the previously-experienced difficulties (3) on the maintenance of different oxygen-contents in the water of one system. This could be expected in a laboratory arrangement where aerobic and anaerobic conditions in the same waterflow would have to alternate comparatively rapidly.

e. Effects of Waterflow Length and Slope on Elliot Lake Tailings Effluent

The apparatus was extended with two additional troughs. Each of the four troughs was positioned at 16°. The wood waste from the previous experiments was discarded (day 100) and each of the troughs filled with 2 kg fresh, non-sterilized wood-waste, cellulose mix. The effect of the nutrient-IIa flow through one trough was compared with that through three troughs after inoculating both units with micro-organisms as under "d". The tapwater was not micro-filtered. The volumes of the cultures were divided in a 3:1 ratio between the units. One pump with two heads was used to produce the same flowrate through the two units (one with one trough and the other with three troughs). The water inlet in each tank was fed to the bottom of a 35-cm long, 65-mm diameter vertical glass-tube closed at the bottom with a rubber stopper placed at the bottom of each tank. The outlets of the siphons, or pump-intakes, were positioned approximately 5 cm under the water level. This would reduce the water flowrate along the bottom of the tanks to develop anaerobic conditions there. The pH was monitored.

After 13 days (day 113) solution-IIa was discarded and Elliot Lake tailings effluent was pumped in. Approximately 6-L effluent from the one-trough and 18 L from the three-trough system were discarded. The pH, and periodically the dissolved oxygen content, were measured. The treated effluent, filtered through a 0.2-μ filter, was submitted for chemical analyses.

Because of the initial pH-decrease after the fast increase, the flowrate was decreased to 10 mL/min for 3 days (day 122-125) to produce an effect similar to that in the high-ferrous iron solution (day 32-35) recovering from significant iron-hydroxide precipitation.

Fresh tailings-effluent (2 x 50 L) was aerated on the side for 4 days to simulate conditions in the reservoir of an actual abatement system (See

D_1, D_2 day 134, Fig. 4). It was fed in the systems without discarding any effluent from the troughs by connecting a 50-L tank to each one previously used (day 138). Siphons were used for the solution transfer between the tanks. The siphon outlets were also fed to the bottom of 65-mm diameter glass-tubes and the intakes were 5 cm below water level as above. The pH was monitored and the dissolved oxygen content measured periodically. The treated effluents, filtered through a 0.2-μ filter, were submitted for chemical analyses.

The inclination of the one-trough unit was decreased to 4° after 5 days (day 143) to determine (day 145) the effect of a change in trough slope on the water composition.

f. Effects of Sulphate Reducers on Elliot Lake Tailings Effluent

After 7 days (day 138-145) of recirculating the tailings effluent when the pH of the water in each of the units had increased above 5, the bottom layers of each of the four tanks were inoculated with a culture of Desulfovibrio desulphuricans (A.T.C.C. no. 7577) grown in a modified Iverson's medium (9). This was repeated after another 4 days (day 149). When a black precipitate had developed in the bottoms of the tanks after 12 days (day 150) of the start of this experiment, water samples were collected, filtered through a 0.2-μ membrane filter and submitted for analyses. The water was recirculated at various flow rates to determine the effects on the dissolved-oxygen distribution.

After 32 days (day 134-166) contents of the two tanks (C_1, C_2) of the one-trough unit were replaced with fresh tailings effluent. This trough was connected with the other three forming a four-trough unit connected with four tanks (2x C_1 and C_2). The previous experiment determining the effects of gradually mixing fresh tailings effluent in the system on the pH was repeated. The conductivity of the wood-waste effluent was measured periodically (to determine the possible significance of this variable) using a model-31, Y.S.I. conductivity bridge.

RESULTS

EFFECTS OF FLOWRATE VARIATIONS ON pH-5 SOLUTION

The results of the pH-measurements of the solutions flowing through the troughs (A), (B) and glass tubes (A'), (B') are shown in Figure 4.

The pH increased in both systems, (day 0-7), despite the increase of flowrate to 75 or 100 mL/min (day 14-17). However, stopping the flow simulating stagnant conditions (day 19-20), decreased the pH slightly. Resumption of the flow at 50 mL/min (day 21-22) increased the pH again.

The pH of the fresh solution in the troughs levelled off at 7.8 after 7 days and that in the tubes at 7.5 (day 14-23). The results show that the pH of the solution recirculating in the troughs increased significantly faster than that in the tubes. In the troughs pH 7 was reached after 2 days (day 7-9), in the tubes after 6 days, (day 7-13).

EFFECTS OF HIGH-FERROUS IRON ON A pH-3.5 SOLUTION

The increase of the pH in the troughs after introducing solution-IIb was much greater than that in the tubes (day 23). Further, the solution remained slightly coloured, while that in the tubes became clear (day 23). The pH-increasing activity, however, began to decline in the tubes after two days (day 25) and in the troughs after 5 days (day 28). This pH-decrease in the troughs can be connected with the formation of an iron-hydroxide coating over the wood particles in both troughs. The formation started at the inlet and reached the outlet after approximately five days. However, the pH increased again above 5 (day 32-35) in the troughs at 10 mL/min flowrate. At the same time a black precipitate was observed in the Tygon tubing connecting the two troughs. No such precipitate was formed in the glass-tube arrangement where the pH remained at the same level or even declined slightly. The formation of the precipitate must be attributed to anaerobic or low oxygen conditions in the troughs sufficient for growth of sulphate-reducing organisms. Tap water was used to replace water lost by evaporation. Tests for the presence of sulphate-reducing organisms were positive so that they may have been introduced by the tap water. The wood mix had been sterilized. The results show the strong recovery potential from adverse conditions in the trough arrangement.

Because the organisms in the glass tubes had apparently become inactive, and to eliminate the effects of a heavy iron-precipitate on pH-increases in the next experiment, the wood mix was replaced (day 35).

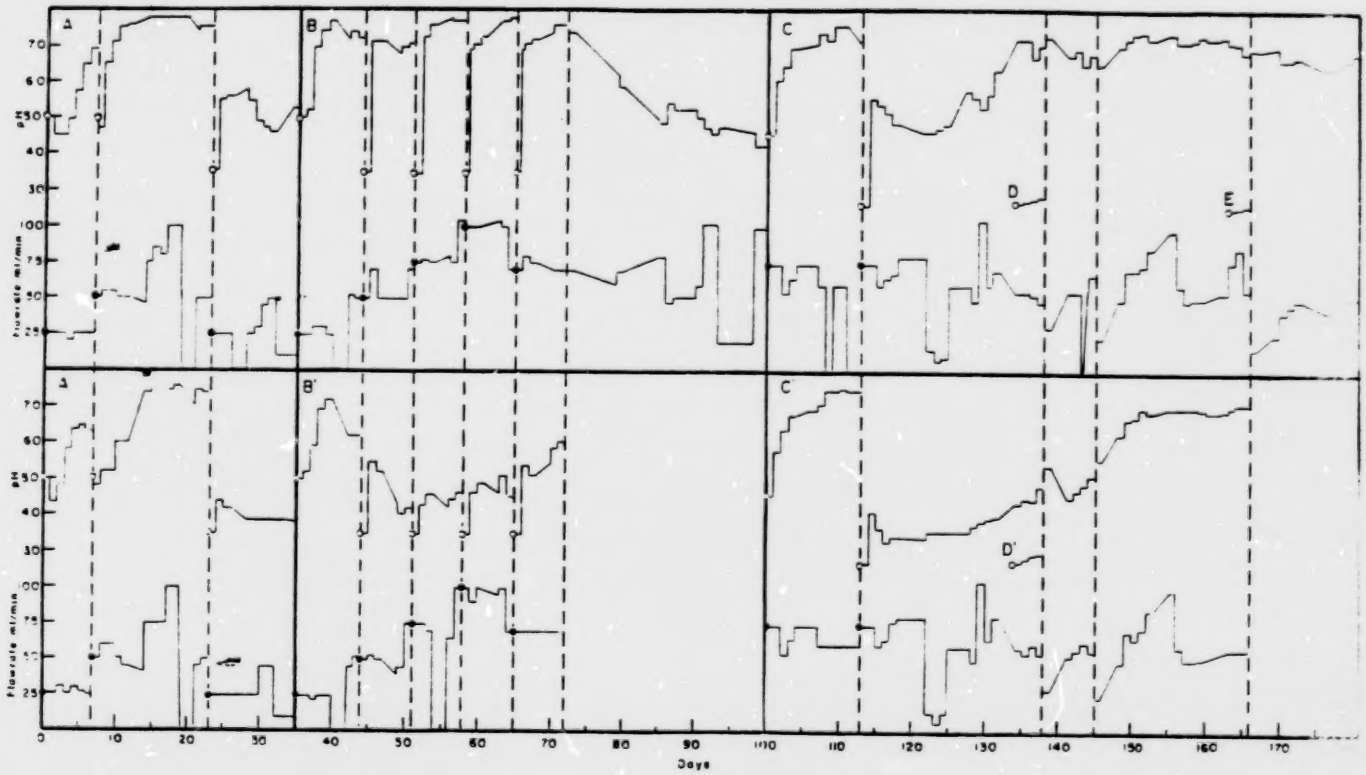

Figure 4. Variations in pH-values and flowrates of effluents from wood wastes

¦ - Change in treatment or condition

| - Replenishment of wood waste

o - initial pH-value of solution

• - initial flowrate of experiment

A,B - wood waste in 2.4 m troughs

A',B' - wood waste in 4.8 m glass tubes

C - wood waste in 3.6 m trough

C' - wood waste in 1.2 m trough

D,D' - tailings effluent, aeration effect

E - tailings effluent aeration effect, for wood waste in 5.6 m trough

ESTIMATION OF MAXIMUM FLOWRATE FOR pH-3.5 ABATEMENT

The pH-increase during the first 5 days of the experiment (day 35-40) using a 25-mL/min flowrate was similar to that obtained in the previous experiments. The pH-increase in the troughs was faster than that in the tubes. The initial pH 5 had not decreased, however, as in day 1-3. This might have been caused by using a different batch of wood waste; although the same softwood, it was probably older and might have been leached to a greater extent by rain.

The effects of a temporary shutdown of the pumps (day 40-41), resulting in a pH-decrease, however, were similar to those in the previous experiments (eg. day 20). The pH increased above 5 in both troughs and tubes at the subsequent 50-mL/min flowrate (day 45). The pH-increase in the troughs, however, was significantly greater than that in the tubes in which the pH decreased in subsequent days (day 46-50). White fungal growth was observed amidst the wood grains in the tubes (day 46), but not in the troughs.

After 3 days at 50 mL/min (day 47-48) a black precipitate and sulphide smell developed in the troughs. At the same time the pH had decreased. Aeration was increased (day 49) which increased the pH again. The pH in the tubes had decreased to 4.

At 75 and 100 mL/min (respectively day 51-58 and 58-65) the pH of the water in the troughs increased to values above 7 in one day. At 100 mL/min the pH increased from 3.5 to 6.95 in 4 hours or possibly less. The pH-increase in the tubes had been much slower. No sulphide smell developed at these flowrates. Visible fungal growth had developed in the wood waste above the water level in the troughs (day 54-56).

In solution-IIa containing ferric nitrate and sodium sulphate (day 65-72) most of the iron precipitated as hydroxide in the tanks. The total iron and sulphate contents had been respectively 237 mg/L and 508 mg/L. However, after filtering the solution through a 0.2-μ membrane filter, 0.2 mg/L Fe and 325 mg/L SO_4 remained in solution. The pH in the troughs increased from 3.5 to 6.86 in 4 hours or less (day 65). Although the pH increased above 6, the slow pH-increase in the glass tubes was clear, and that part of the experiment was discontinued.

The experiments in the period day 72-100 attempted to detect the cause of the pH-decrease in the troughs after including the tank from the glass tubes into the trough system. The decrease might be caused by toxic

metabolites from excessive fungal-growth in the tubes, oxygen deficiency due to the arrangement producing anaerobic conditions in the tanks or material exhaustion.

At day 72 the wood waste had become severely degraded and smelled like compost. Even when the flow rate was decreased to 50 mL/min (day 86-91) or later to 20 mL/min (day 93-98) or when aeration increased (day 92), the pH-decrease continued. The dissolved oxygen content of the bottom layer of tank (C_2) was 13% saturation O_2, while that in the top layer was 40% saturation O_2. Effluent from the troughs had a 48% saturation oxygen content compared with fresh tapwater 100% saturation O_2. Only by increasing the flowrate to 100 mL/min the dissolved oxygen content of the top layer increased to 59% saturation O_2. Discarding the solutions in both tanks, flushing the system (day 98) at 150 mL/min with tap water for 3 hours, recirculating tap water adjusted to pH 3.5 with 10% (v/v) HNO_3 after inoculating the wood with fresh microbial cultures, did not increase the pH above 4.3.

The compost-like smell suggested exhaustion of the wood mix. However, absorption of toxic materials (fungal-metabolites) into the wood can not be excluded.

EFFECTS OF WATERFLOW LENGTH AND SLOPE ON ELLIOT LAKE TAILINGS EFFLUENT

The variations in pH and water flowrate in the one-trough (C') and three-trough systems (C) are shown in Figure 4. The pH-increase in the three-trough system was slightly faster than that in the one trough. The pH decreases in (C) (day 108 and 111) originated in unintentional interruption of waterflow. The pH levelled off in both systems at approximately 7.75.

The pH-increase of the tailings effluent (day 114) in one trough was significantly smaller than that in the three troughs. The water compositions of the two units at different stages in the experiments are listed in Table 1. The compositions at day 134 are those of the fresh tailings effluent (D,D').

The decrease in iron contents (day 113-121) was the same in both units and can be attributed to iron-hydroxide precipitation. Purification in the three-trough unit in which U, Th and Ra became undetectable and SO_4 was almost halved, was greater than that in the one-trough unit.

TABLE 1. Composition of tailings effluent after treatment in different wood-waste lengths*

Day no.	Days	One-Trough Unit						Three-Trough Unit					
		pH	Fe	SO_4	U	Th	Ra	pH	Fe	SO_4	U	Th	Ra
				g/L			pCi/L			g/L			pCi/L
113	0	2.70	0.087	1.59	0.007	0.002		2.70	0.087	1.59	0.007	0.002	
114	1	4.15	0.002	1.26	0.0005	0.0005		5.65	0.002	0.84	<0.0001	<0.0005	
121	8	3.57	0.002	1.38	0.0009	0.0005		4.65	0.002	0.90	<0.0001	<0.0005	
134	0	4.83	0.02	1.35	0.0054	0.0005	210	7.06	0.02	1.35	0.0054	0.0005	210
138	4	5.42	0.0004	1.35	<0.0001		15	7.23	0.0001	0.81	<0.0001		10
150	16	6.69	<0.0001	1.41	<0.0001		15	7.33	0.0001	0.81	<0.0001		15

*Analyses by members of Chemical Laboratory, Mineral Sciences Laboratories, CANMET, Energy, Mines and Resources Canada.

The pH of the one-trough unit did not increase above 5 before connecting it with another tank containing 50-L tailings effluent (day 138). The pH in the three-trough unit remained below 5 for 8 days before recovery (day 125-138).

Aeration of 2 x 50 L fresh tailings-effluent (Fig. 4, resp. D, D') increased the pH slightly (2.67 to 2.95), but oxidized most ferrous iron (e.g. 3.5 mg/L to 0.5 mg/L, resp. day 135, 136) and decreased in the same time the total iron content from 17 mg/L to 9 mg/L by precipitating iron hydroxide. After connecting these tanks (D, D^1) with those used, and decreasing the flow rate to 30 mL/min, the pH in both units increased respectively to 5.42 and 7.23 (day 138). The iron content in the three-trough unit had also decreased more than that in the one-trough unit (Table 1).

Because a sulphide smell began to develop, the flowrate was increased to 50 mL/min (day 141-145). ph measurements at different locations in the three-trough unit indicated a relation in the pH-gradient over 3.6-m wood

waste (3 trough lengths). The pH-difference between out- and in-flowing water was 2.35 pH-units (7.23-4.88; day 138) at 30 mL/min flowrate. At 56 mL/min flowrate the pH-difference was 1.91 pH-units (6.84-4.93; day 142).

The decrease in inclination of the one-trough unit did not show a significant effect (day 143-145). The wood volume, however, was almost submerged. If a level position must be used, a greater wood-volume is required, and a mixing of wood waste with aerated water between the baffle-plates should be prevented by a screen on top of each overflow baffle.

EFFECTS OF SULPHATE REDUCERS ON ELLIOT LAKE TAILINGS EFFLUENT

The dissolved oxygen contents before and after inoculating the tanks (resp. days 145 and 148-161) with sulphate reducers are listed in Table 2. Aeration was not varied.

TABLE 2. Dissolved oxygen contents of various water layers in wood treatment units

Day	Unit	Flow-rate mL/min	pH	Dissolved oxygen content in per cent saturation					pH
				Trough exit	Tanks C_1/bottom	C_1/top	C_2/bottom	C_2/top	Trough inlet	
145	(1)	25	5.58	38.5	38.5	32.1	28.2	41		
145	(3)		6.51	16.7	2.6	ND	3.8	ND		
148	(1)	50	6.34	55.5	35.8	29.6	17.3	32.1	39.5	
148	(3)		6.98	43.2	ND	ND	ND	ND	13.6	
149	(1)	70	6.60	61.7					18.5	6.69
149	(3)		7.20	45.0					37.0	6.97
150	(1)	70	6.69	53.8					28.2	6.80
150	(3)		7.33	42.3					39.7	7.13
155	(1)	95	6.85	38.8	30.6	27.1	28.2	21.2	24.7	6.67
155	(3)		7.34	44.7	36.5	28.2	23.5	23.5	31.8	7.05
161	(1)	50	6.89	14.3	ND	ND	9.1	ND	3.9	6.96
161	(3)		7.26	42.9	10.4	10.4	10.4	2.6	15.6	7.26

ND-not detectable

A slight sulphide-smell had already developed in tank (C_1) of the three-trough unit at the time of inoculation with sulphate reducers (day 145). This increased considerably after inoculation while the contents of the tanks connected with the three-trough unit turned black. Only the tank bottoms of the one-trough unit became black after inoculation. The tank contents of this unit turned black after the last flowrate decrease to 50 mL/min (day 161).

The introduction of the sulphate reducers did not affect the water composition significantly. They may have been present already before inoculation, at least, in the three-trough unit. Table 2 shows that the dissolved oxygen contents increased in both units due to the aeration in the baffle-units, the "trough-exit"-contents being higher than those of the inlets. The oxygen contents in different locations of the three-trough unit were affected by a change in the water flowrate. They were below detection in the tanks at 50 mL/min flowrate (day 148), but increased significantly with a flowrate increase to 95 mL/min. They decreased again when the flowrate was slowed down to 50 mL/min (day 161). The oxygen contents of the one-trough unit indicate that more factors then the flow water are involved. The oxygen contents of the trough-outlet of this unit increased almost linearly with the water flowrate from 25, to 50 to 70 mL/min (resp. day 145, 148 and 149), however, they then decreased gradually. The oxygen decrease took place notwithstanding the flow rate increase to 95 mL/min or decrease to 50 mL/min. The depletion of the oxygen content shown by the three-trough unit (day 145-148) occurred later in the one-trough unit when the pH had increased sufficiently (above 5) allowing a marked growth of the sulphate- reducing population. The oxygen absorbance in the one-trough unit during increased flowrate must be attributed to species accompanying the sulphate reducers. Purification of cultures of sulphate reducers had appeared difficult probably because of synergistic relationships comparable with those involved in purifying cellulolytic cultures (4).

The results of the gradual mixing of the fresh tailings effluent (E, Fig. 4) in the four-trough system were not different from those of the first experiment in gradually mixing fresh tailings. Stagnancy for 14 days (day 181-195, not shown) decreased the pH from 6.78 to 6.20. Resumption of flow, however, increased the value in one day to 7.08.

The conductivity of the wood-waste effluent was approximately 1550 micromhos and did not vary significantly, decreasing to a minimum of 1300 micromhos.

DISCUSSION AND CONCLUSIONS

FACTORS CONSIDERED FOR PROCESS APPLICABILITY

The following factors were considered for the practical application of the wood-degradation process to acid mine-water pollution-abatement.

a. The water flowrate that can maintain the process in a specific volume of wood waste is the principal factor to be determined. Theoretically, information about the relationship between water flowrate, wood-waste grain-size (surface area) and microbial action would be required. However, these relationships are not only difficult to determine, but also to apply. The experiments were, therefore, based on practical considerations.

b. The water flowrate through the wood waste is limited by the wood grain (pore) size and by the microbial action. If the flowrate exceeds that due to the grain (pore) limits, waterflow over the wood-surface in the ditch will decrease the abating performance of the system. The flowrate increases in the baffle windows, which are significantly smaller in size than the other cross-sections in the ditch (trough), so that coarse gravel allowing this faster flow has to be piled against the windows (p. 3).

c. The design of the waterflow through the wood waste in the ditch was based on the results of a study on the microbial-process principles (4). A design using baffles and a sloping bottom was selected because of ease of construction. The slope was arbitrary and might not be required if the water is aerated (p. 10). The exact ratio between anaerobic and aerobic conditions could not be determined in the experiments. However, aerobic conditions should prevail over anaerobic (4), therefore aeration was applied. The performance of this design would be compared with that of a waterflow through a wood-waste column. This might provide information on the effect of a significant wood surface-area increase. Measurement of oxygen contents of the solutions at different locations in the trough system was considered. However, the variations in the oxygen-content

intended in the design of the waterflow direction (anaerobic, aerobic) could be determined more accurately in a larger size arrangement, in which also the recirculation effect would be eliminated. Measurements of the oxygen-contents at various locations in the troughs would have to use micro-procedures. Furthermore, the flow direction in the troughs is not exactly the same as in a ditch because wood-waste grain-sizes cannot be reduced.

d. Although the concept of 'water flowrate' refers to the water volume passing through a two-dimensional section, a minimum travel length for the microbial action is required. The water travel length, although obviously limited towards a minimum, would also be connected with the quantity of (contaminant) precipitate formed on the wood (preventing microbial action) and thus the frequency to replace it. The minimum travel length required for the microbial action is extended by wood surface contamination because it prevents this action. However, data about the microbial action on a wood surface area are lacking and can be expected to be difficult to apply to practical conditions because of varying grain sizes in the wood waste. Generally, the longer path in the wood the solution has to travel, the greater the opportunity for microbial action, the higher the allowable water flowrate subjected to this action and also the greater the "contaminant storage" capacity or the longer a supply of wood waste would last.

e. The combination of microbial species and nature of wood waste (grain size, tree species) producing optimum pH-increase and wood-degradation rates were not determined. The experiments would be lengthy, and indications have not yet been obtained that a practical process might be feasible. During the experiments on the principles involved in the process (4) it was expected that the rate of pH-increase and cellulose degradation would probably be increased by a factor 5 to 10 using a natural combination of microbial species observed to produce the required process. The composition of this combination is not known. Weekly recirculation was applied in the experiments because information about the effects of variations of flowrate and composition of the water, of aeration and sulphate-reducing organisms, could be obtained. Experiments using the length of a wood-waste volume required for flushing the water as in an

actual process, was not practical in the available laboratory space. Generally, the grain sizes of the wood waste are those used in an actual abatement process. Size reduction of experiments for simulation purposes should ideally be kept to a minimum because the wood-waste size can not be reduced. In a field arrangment the experimental and "pilot-size"aspects would be combined. This would reduce this discrepancy. Small scale simulation of waterflow properties is only valid in models in which everything is reduced in size (weirs, dikes, etc.).

The nature of the wood waste was also not varied because the experiments would be lengthy and it would be more practical to experiment with this variable in a larger-size experiment. Hardwood has a higher cellulose and nutrient content than softwood (10,11) and should be preferred because the microbial process uses cellulose. However, the grain sizes of hardwood waste are significantly smaller than that of softwood waste ("sawdust"; grainsize depending on the thickness of the saw) so that the maximum flowrate (Appendix 2) and oxygen content of the water could be expected to be lower. Softwood waste was used because it was readily available. The amount of cellulose waste mixed in the wood could also be optimized. However, a ratio was used that did not affect the maximum flowrate significantly; larger quantities would have a clogging effect.

CONCLUSIONS

The following conclusions are used to design plans for the completion of experiments to apply the wood-degradation process to actual acid mine-water pollution-abatement.

1. The wood-waste mix should be partly submerged in the waterflow

The superior performance of the wood waste in the troughs concerning acidity-decrease over that in the tubes is based on the extent of water contact with the wood particles. The wood waste in the tubes was loosely packed to prevent clogging, and to allow the water to trickle over as many particles as possible. In the troughs the greater part of the wood was submerged leaving only 0.5 to 2 cm of the mass above the water level. The submergence of the wood provides a longer and more intense contact with the water than that in the trickling action in the tubes where it produces a periodic thin water-film over the wood. Anaerobic conditions would have

been created by filling the tubes with water and would be the same as these in the troughs below the water-level (not considering differences in areation methods). The oxygen content of the water in the tubes was thus greater than that in the troughs. The difference between these conditions was indicated by abundant fungal growth in the glass tubes. This growth was present in the troughs only in the layer of wood above the water level having a significantly greater air content than the water-soaked part. The detrimental effects of excessive aeration of wood waste cannot be eliminated merely by extending the length of wood waste as in the tubes not withstanding experiments comparing the one- with the three-trough unit showed that extended length affected the pH-increase favourably.

2. The length of the ditch should be maximal, but its depth limited

The superior performance of the three-trough unit over that of one-trough in cleaning up pollution (p. 14) indicates that ditch length should be maximal. The experiments showed however that the effects of different wood volumes on the pH-increase are not necessarily proportional to those of the wood lengths. This indicates that length, width and depth of the wood waste are distinct factors in the process.

The initial pH-increase and recovery from pH-2.7 water in the three-trough unit was significantly greater than that in the one-trough unit (day 115-137). However, the pH-increase from the high-ferrous solution using the two-trough unit (day 23-35A) was greater than that of the comparable tailings-effluent in the one-trough unit (day 113-130C') notwithstanding they both contained 2-kg wood mix. It is possible, therefore, that the wood waste layer near the water surface has the greatest effect on the pH-values. This was also suggested by the observations on the extent of degradation of the wood waste. The texture of the wood was almost unaffected in appearance below the water level, dark and degraded near it, and often covered with fungal growth at approximately 1 cm or more above it. This means that the ratio of ditch width to depth must be considered in further experiments, because the thickness of the layer required for optimum microbial action (depth) is not known. Furthermore, depth requirements for the periodic decrease of the oxygen content near and in the baffle windows are not known either.

In order to prevent "channelling" a number of shallow parallel ditches appears more preferable than one wide ditch. Narrow ditches should prevent

the localized formation of low-oxygen conditions that may decrease the pH and precipitate heavy metals as sulphides in the wood by growth of anaerobic sulphate-reducers. However, the arrangement is probably not practical and one ditch with width to depth ratio optimized is preferable for construction.

A parallel arrangement of two or more shallow ditch units may solve the problem of replenishing the wood waste which would interrupt the process. Tailings effluents (or mine-water) can be divided into a main stream flowing through an active ditch unit while a small stream can activate fresh wood waste (feed-back if required). The design of the waterflow through the wood waste should keep modifications of existing drainage conditions to a minimum.

3. Low pH-values in the feed create lag-times in the process

The previously experienced (4) irregular pH-increase from low pH-values were indicated again by flowing fresh tailings-effluent (pH-2.7) in the wood waste. Eight days were required to raise the pH above 5 in the three-trough system (day 117-125). This lag-time was decreased or eliminated by a gradual slow mix with a system operating at higher pH-values (day 138-142). The pH of the three-trough unit remained above 6.5 in these conditions, while that of the one-trough unit decreased gradually to a minimum 4.55 (day 141) before increasing. This was repeated (day 166-180) using a four-trough system.

4. High iron-hydroxide precipitation on the wood retards the process

The introduction of a high-ferrous iron load at 25 mL/min (day 23A) showed the detrimental effect of a formation of iron hydroxides on the wood particles. Because the pH had increased in one day above 5 in the troughs (day 24A, 113C), a regular waterflow flushing out the high-iron water might have cleared the wood waste for further microbial action. However, recirculation in the systems promoted the development of a coating of iron-hydroxide precipitate which impeded microbial growth, resulting in a pH-decrease. Neither the pH-3.5 level nor the water flowrate were the cause for the decline in microbial activity. In the experiment using a solution without high (ferrous) iron, the pH increased even at 100 mL/min (day 58). The process, therefore, cannot tolerate a prolonged flow of water having a high ferrous-iron content that precipitates as a hydroxide

on the wood. As much iron as possible should be precipitated as hydroxide by aeration of the polluted water before entering the wood-treatment process. This was also indicated by the results of introducing Elliot Lake tailings effluent which had additionally a low pH 2.7 (day 113 C, C').

The reservoir in front of the dam should therefore be aerated to decrease the ferrous-iron content of the water, precipitate iron-hydroxides and increase the pH as much as possible. Aeration of tailings effluents (day 134-138) oxidized all ferrous iron, precipitated some iron hydroxide, but hardly affected the pH .

5. The water flowrate should be adjusted according to the pH-level

Several factors, such as dissolved oxygen content, state of process and wood degradation, etc. are involved in the relationship between the water flowrate and the pH. The water flowrate variations, often caused by uncontrollable factors, such as sensitivity of pump control, accumulation of microbial growth in the tubing producing temporary or permanent clogging, did not provide clear unilateral evidence on the relationships. However, the pH decreased at high pH levels when the waterflow was reduced to stagnancy. It produced low-oxygen conditions which decreased the pH (day 19-21; 40-41; 54-55(B'); 108 and 111 C).

At low pH-levels, however, a decrease in flowrate (not to stagnancy) sometimes increased the pH (day 32-34A; 122-125C; 138C). Low flowrates (maximum 50 mL/min in 2.4 m wood length) promote low-oxygen conditions, and therefore, the production of iron sulphide observed as black precipitate locally in the wood. Whether this prevents or converts the iron-hydroxide coating is not known. Previous experiments (4) suggested ion-exchange in the action of pH-increasers in the range pH 3.5-5.8, and oxidation at higher pH-values. This would explain the requirement for high flowrates or aeration (oxidation) at pH-levels higher than 6, and the favourable effect of low flowrates (low-oxygen conditions promoting ion-exchange) at low pH-values. Cellulose reduction was connected with cellullolytic action. The exact metabolic activity, however, is not known because certain species could increase as well as decrease the pH, depending on environmental conditions (4). These results, however, suggest that the flow design in the ditch should produce a variation in the oxygen content of the water. The oxygen content of the water depends on the flowrate, the microbial growth (Table 2) and on the extent of aeration between the baffle plates.

An increase in aeration raised the dissolved-oxygen content of the trough effluent from 48.4% to 59% saturation 0_2 (day 92), while the oxygen content of the bottom of the tank was 15.7% saturation 0_2, and the water flowing into the troughs was 40% saturated with oxygen. The oxygen content will be affected also by the extent the microbial action absorbs oxygen. This absorption caused by the growth of a microbial sulphate-reducing population was greater than the effect of flowrate increase provided the pH permitted microbial growth (Table 2). A determination of these relationships would be too lengthy and impractical at this stage of the project.

The flowrate should be based on that preferred by microbial action in a length of wood waste, selected in view of average-yearly polluted water volume that must be treated. It should be possible to vary the flow according to the pH-level, and create a gradation in the aeration with its maximum at the ditch outlet. Because the pH of the reservoir water can be expected to be always low, localization of a preferable position of the pH-electrode controlling the water flowrate must be established by an experiment using a long trough or ditch.

The relationship between pH and flowrate, suggested by the experiments, may reflect that of natural conditions. An increase in water volume due to rain or melting snow would increase the pH because of dilution of the acid in the water; droughts (evaporation, low flowrate) would decrease the pH because of concentration.

6. <u>The range of flowrates preferable for microbial action is 0.3 - 0.45 mL/min/cm^2 along a 2.4 m length of wood waste</u>

A flowrate of 50 mL/min was preferred for microbial action, or $^{50}/_{25}$ = 2 mL/min/cm^2 through baffle windows (cross-section 2.5 x 10 cm = 25 cm^2, p3), or $^{50}/_{150}$ = 0.33 mL/min/cm^2 in the troughs (cross-section 15 x 10 cm = 150 cm^2) for a minimum travel length of 240 cm (combined trough lengths). This value was indicated by the pH-recovery from 3.5 to 5.5 in one day (day 23A) at a flowrate of 25 mL/min of water with a high ferrous-iron content, but to pH-values higher than 7 in one day at 50 mL/min (day 44A), 75 mL/min (day 51A) and 100 mL/min (day 58A) of solutions without high ferrous-iron. Flowrates higher than 50 mL/min might decrease the possibility to recover from adverse conditions. However, 68 mL/min (resp. 2.72 mL/min/cm^2 through baffle windows or 0.45 mL/min/cm^2 in the

troughs) could possibly be used (day 50A; 65-71A) when other variables would be optimized as described on p. 28/29.

A 50-mL/min or 0.3-mL/min/cm^2 flowrate is the lower limit because of the development of low-oxygen conditions and a pH-decrease (day 47-48). The extent of unfavourable conditions could be improved by increasing the aeration (day 21, 49). A higher flowrate e.g. 68 mL/min or 0.45 mL/min/cm^2 prevented also the development of pH-decreasing low-oxygen conditions (day 50). These conditions and the formation of a sulphide-smelling black precipitate developed in the three-trough unit using 50 mL/min flowrate but not in the one-trough unit. This flow rate through the length of three troughs appeared to be too low to prevent the decrease of oxygen in the water. It is possible, therefore, that the wood-length factor is connected with the microbial action absorbing oxygen. A comparatively long length requires a high flowrate (oxygen content) to offset the effect of microbial oxygen-absorption. This might also suggest that the "segmentation" concept (p. 36) would be valid to a certain extent.

The maximum physical flowrate was estimated at 5-7 mL (av. 6 mL)/min/cm^2 (Appendix 2). The maximum flowrate in the troughs due to baffle windows (25cm^2) would, therefore, be 25 x 6 mL/min = 150 mL/min and that in the glasstubes 28.3 x 6 mL/min = 170 mL/min. The maximum flowrate in the troughs without baffles could be 15 x 10 x 6 mL/min = 900 mL/min.

Information about a pH-gradient along a length of wood waste indicate that on extrapolating 2.35 pH units at 30 mL/min and 1.91 pH-units at 56 mL/min (p. 15), the pH-increase would be limited by a flow of 169 mL/min or higher. This is higher than the maximum 150 mL/min through the baffle windows, but made possible by the application of a gravel bed (see p. 18, 37). If these values are indicative of a maximum pH-gradient, a length of $\frac{(7.5-2.5)}{1.91}$ x 3.6 m (length of three-trough unit that produced 1.91 pH - unit increase at 56 mL/min)= 9.4 m would be required to raise the pH from 2.5 to 7.5 at 0.37 mL/min/cm^2 (56 mL/min), and it would take a water unit 1.8 days ($\frac{940}{0.37}$ min) to travel this length.

One week recirculation at 0.33 mL/min/cm^2 (or 50 mL/min) is equivalent to flushing water along a 43.2 m wood-waste length. The same at 0.45 or 0.50 mL/min/cm^2 (or resp. 68, 75 mL/min) flowrates constitute lengths of 58.9 and 65.5 m respectively (p. 38).

7. The yearly effluents from 100-200 acres of tailings or 600 L/h mine-water might be treated practically with the microbial wood-degradation process according to the water recirculation experiments

Ways of projecting the results of the experiments into a practical process have been considered in Appendix 3 using a waterflow through two troughs. They indicate the possibility of treating the effluents from small to medium tailings areas (approximately 200 acres) in two parallel 50-m long ditches having each a 3-m^2 cross-section. This estimate, based on several assumptions, can be refined for a particular location because of known-factor values. The estimate can be used for regulating the water flowrate through the ditch with wood waste in view of yearly accumulation of effluent in a reservoir preceeding this ditch. However, an accurate determination of the relationships between flowrates, pH-levels and pH-gradients was not possible in the lab experiments. The average yearly precipitation and evaporation were estimates (p. 32) that will vary considerably with each location. Suppose, the yearly effluent volume would be twice as high as estimated. The experiments indicated that the microbial action would still be sufficient (2 x 50 mL/min = 100 mL/min) so that it would be a matter of adapting other variables such as wood-waste grain-size and ditch size to accommodate a treatment of greater effluent volume.

Lack of water in droughts should be avoided by applying a water flow-rate that maintains a steady water supply from a reservoir, and equalizes the flow from periods of rainfall, melting snow and droughts. The extent of aeration will, therefore, also depend on the yearly water flowrate produced by the reservoir because of reduced pH variations in the flow equalization.

Generally, the ditch length and/or use of several parallel ditches, the number of baffles, baffle-window size, gravel-bed size, aeration, nature and grain size of the wood waste, and composition of microbial inoculate can be varied to optimize process performance.

8. Optimization of composition of microbial population should be directed to process-maintainance

The fast pH-increase from 3.5 to 5.5 (day 24) using a high ferrous-iron solution and those at greater flowrates from the same pH (3.5), using solutions without much (ferrous) iron, suggest that various microbial species, disregarded in the study on the process principles (4), might contribute to process maintainance (removal of toxic metabolites, production of required trace nutrients, etc.) rather than to the rate of pH-increase. The random combination of pH-increasing and cellulolytic species, used in the present experiments, could neutralize pH-3.5 water in a few hours to one day. However, a pH-decrease occurred after the initial increase in the tailings effluent (day 114). This was also observed in the previous study (4), and was a matter of irregular metabolic functions. It is not known which combination of species is required to act at an optimum rate on a tailings effluent and maintain the action. The random combination of organisms used in the experiments was isolated from one source. Species occurring in that source that were not included in the experiments can be expected to have specific functions in the ecology.

9. Optimization of water purification by microbial heavy-metal precipitation is limited

If a system has the highest possible pH-increase and cellulose degradation rates, conditions for growth of sulphate reducers can be optimized primarly mechanically (improved anaerobic conditions). It may also be possible to improve the extent of precipitation of various heavy metals with different microbial species (combination) in a lab-scale experiment. Similarly the effects of various microbial metabolites (depending on the nature of the wood mix) on this precipitation are not known. However, a study of these factors is justified only if a practical process with a high degree of efficiency has been developed.

10. Limitations of the process

The sizes and location of the natural drainage creek and basin should allow the construction of reservoir, ditches and settling lagoons. Effluents from tailings deposits partly submerged, or in close proximity to a lake can not be treated by the wood-waste process. Furthermore, waterflow through larger tailings areas is subject to many factors of

varying topography. The comparatively simple relationship between the precipitation on a surface equals the run-off in a ditch is not valid any longer, and the process may be suitable only locally.

The process can not be left unattended for indefinite lengths of time. Although automatic regulators based on monitoring key-variables can be considered (p. 42), the degradation period of the wood is limited and requires periodic replacement.

The limited effluent-volume that can be treated as well as the process-service requirement may restrict the use of the wood-waste method when compared with other feasibilities based on a study of processes producing natural abating-anomalies in the weathering patterns of tailings deposits, such as the use of a grid of augerholes filled with limestone having a particular grain size mixture (12).

Although the experiments did not produce results unfavourable for the practical application of the process, no information could be obtained on the effect of flushing instead of recirculating the solutions (p. 39). The differences between the results using one-trough and three-trough systems indicated the need for a longer wood volume than that used in the lab experiments, to evaluate the effect of flushing. The pH-increase at the beginning of each run might be indicative of favourable results, yet recirculation may also have extended the use of metabolic nutrients. Definite evidence in this respect, is therefore still required. The previous analyses (4) of the natural process, followed by a synthesis of the results into a practical system in the present work, is an example of the method to use anomalies in natural processes for acid mine-water pollution abatement.

FURTHER EXPERIMENTS REQUIRED FOR DESIGNING THE PRACTICAL PROCESS

1. Continuation of the trough experiments by a field experiment using a long wood volume might be considered because of the apparent simplicity and low costs of the work. For this purpose, two ponds simulating a tailings area and effluent reservoir can be connected with two settling ponds by a channel (ditch). Each unit may be constructed of a plastic lining held up by wooden or concrete sides. The channel construction could contain three parallel units having different shapes of cross-section. Its size could be 25 m long, 250 cm wide and 45 cm deep. Although the experiment could use a long length of troughs (p. 5), it is preferable to enlarge the

cross-section at the same time for greater accuracy of pH-gradient measurement. The total length of channel and ponds would be approximately 65 m. Monitor-control instrumentation could be tried out, and chemical analyses would contribute information to improve a flexible design (baffle frequency, water flowrate, pH-limits, aeration rate, etc.) of a field experiment (See Appendix 4).

2. The following may be considered for process optimization:

a. The effects of possibly-toxic, but commonly used, substances such as soaps, detergents, oils, etc. on the functioning of the microbial population should be determined. The experiments can be connected with and partly included in those under (c). They can be started in the laboratory and extended in the field arrangement.

b. The effects of variations in grain sizes and composition of wood waste on the degradation rate (pH-increase) and capacity should be determined.

c. Experiments on the ecology of the microbial population producing optimum degradation rate and maintainance of the process could be designed:

(c_1). The difference between the composition of the inoculate and the population inhabiting the wood mix or the settling lagoons after a certain period of use should be determined.

(c_2). The pH-increase rate of one species versus that of its combination with one or more relevant species using an "Ecologen" mixed-culture apparatus (New-Brunswick Co.) should be determined. The selection of species should be based on the results of (c_1) and (a), e.g. on the determination of the toxic level of a major pH-increaser; in this respect, the effect of its combination with a species known to eliminate a particular possibly-toxic substance should be determined. Certain pseudomonads and nocardias acting on benzene, naphtalene, phenols, cresol, fats, etc. Further, the effects of species producing "cavitomic cotton" (13), raising the pH above 9, might also be considered in this respect.

(c_3). Because the "purified" water can be expected still to contain a surplus H_2S or other soluble sulphides, the elimination of these compounds by microbial action (e.g. possible growth and action of sulphur bacteria such as Chlorobium, Thiosarcina, Thiospirillus etc. in the lagoon's effluent) or by a practical use in the mining operation chemically, should be considered.

The favourable results obtained in the present work were required not only to justify, but also to design a field-experiment (Appendix 4). When such an experiment also gives favourable results, lab experiments sub ($2c_1$) followed by those sub (2a) could be carried out. The other lab experiments, possibly connected with verification of their results in the field arrangement, are only justified if an actual process is planned.

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APPENDIX I

Estimate of average annual effluent volume from abandonned tailings area

An annual precipitation of 100 cm, such as occurs in the N.E. Ontario-N.W. Quebec mining district, will be assumed. This is subject to 75% evaporation and seepage explained below, leaving 25 mL/cm^2/year or 482 L/min per km^2 to be treated.

The annual evaporation is a factor subject to may different conditions and, therefore, liable to have a wide range of values. Apart from atmospheric conditions such as temperature, cloud cover and wind (air displacement rate), drainage through subsoil and bedrock fissures contribute to the part of precipitation that evaporates or escapes as run-off. Studies in this respect have been made on soils because the ratio between water loss and retention in soils is of importance to agriculture. The drainage depends on the diffusivity through the soil. Gardner et al. (14) found that water lost by evaporation varied from 100% of the total for light and most frequent daily precipitation, to 31.2% for heavy precipitation added every 20 days. The greater the precipitation, the more water is saved from evaporation loss because of deeper seepage into the soil. Almost all water is lost from low precipitations. The evaporation decreases drastically and suddenly with depth into the soil. The average between these extremes is $\frac{100\% + 31.2\%}{2} = 65.6\%$. This is similar to the average loss of 64.3% measured in a sandy loam. This value increases to 78.8% for soils having less drainage (less penetration) such as loam (14). Vegetation increases the evaporation (17). Evaporation in the two-trough system in the lab experiments was significant, and required daily additions to maintain the water volumes.

Drainage through tailings is far greater than through clay-containing soils. However, this drainage should be stopped or minimized by dikes constructed for that purpose (16,17). The tailings can, therefore, be considered to be saturated with water. Once saturated, the water (surplus) from precipitation is subject to evaporation reaching values as high as 100%. A conservative value for evaporation in connection with a yearly water volume to be treated by the wood-waste process is assumed to be 75%. If the tailings impoundment was impervious, drainage water would not be produced; not being impervious, only a part of the drainage forms surface

run-off that will accumulate in a reservoir prior to being treated with wood waste. Even the water in the reservoir is subject to the same evaporation and drainage as that in the tailings. Practically, it is not possible to treat the water directly coming out of the tailings because it is spread over a considerable area forming a kind of drainage basin. Only where a creek has formed, is it feasible to construct a dam for the development of a water reservoir for further wood-waste treatment.

APPENDIX 2

Estimate of maximum flowrate through wood waste

The results of the measurements of flowrates through different wood-waste columns are listed in Table 3 and shown in Figure 5.

TABLE 3

Water flowrates in different wood-waste columns

Column Cross-section cm^2	Length cm	Water flow mL/min	Flowrate $mL/min/cm^2$
7.54	33	561	74.4
7.54	51.5	216.7	28.7
13.20	30	1000	75.8
13.20	58	425	32.2
13.20	65	200	15.2
13.20	81	170	12.9
13.20	100	125	9.5
21.23	35	1500	70.7
21.23	102	245.7	11.6
27.32	50	1039.6	38
27.32	60	678.4	24.8
38.47	37	2200	57.2

The maximum flow rate was estimated at 5-7 $mL/min/cm^2$. The glass tubes in the pollution abatement experiments (p. 6) had a diameter of 60 mm or 28.3 cm^2 cross-section so that a maximum flow rate of approximately 170 mL/min through the tubes could be expected. The maximum rate through the troughs would be greater because the limiting cross-section of the baffle windows were enlarged by the application of gravel. The 60-mm glass tubes had therefore the limiting flow rate.

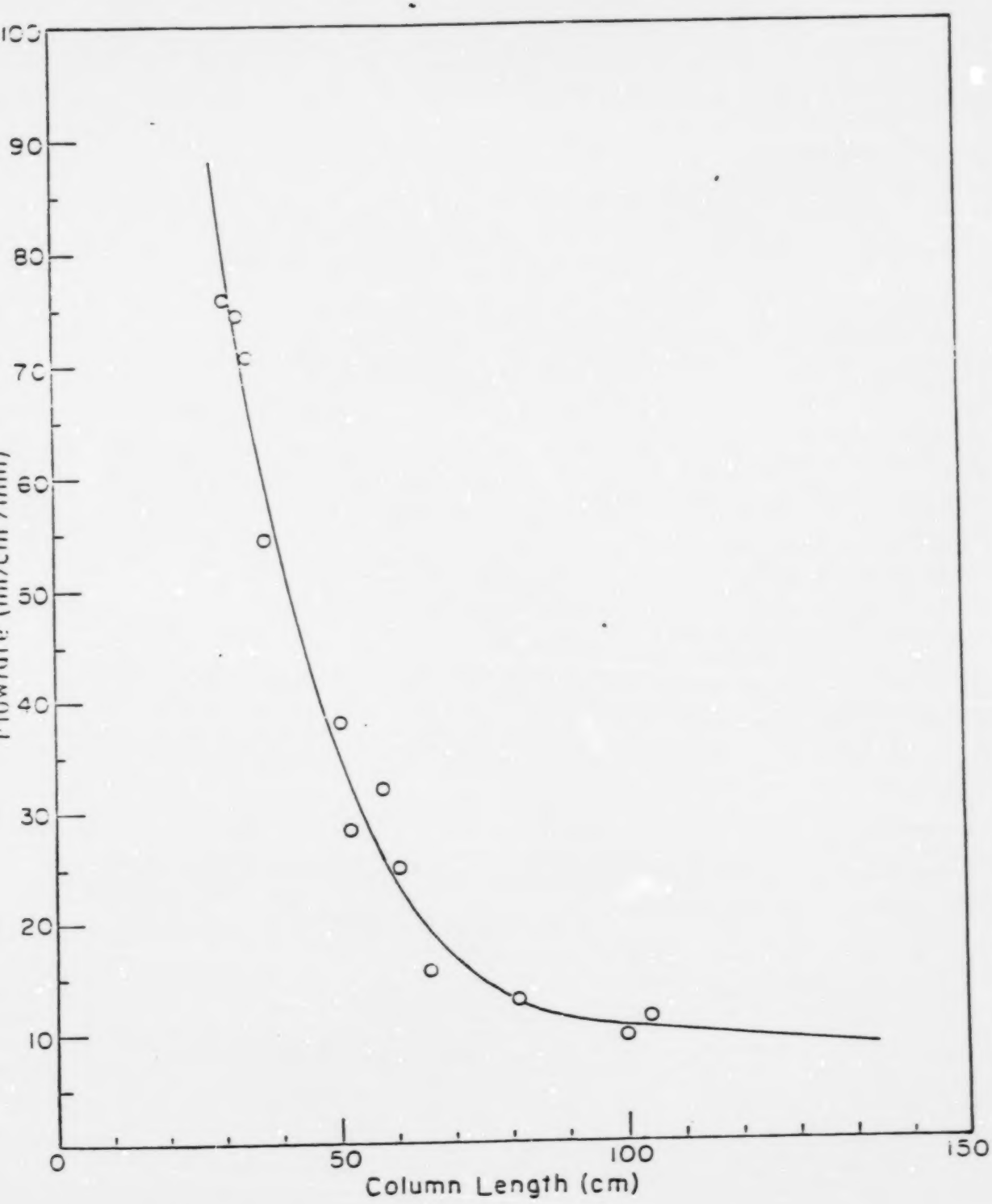

Figure 5. Flowrates through wood waste in different column lengths

APPENDIX 3

Estimation of abatement capacity of wood waste

The length of time required to saturate a wood-waste volume with contaminants (e.g. iron-hydroxide precipitation on a wood surface area at certain water flowrates) is not known. The following estimate refers, therefore, to the abating capacity of the wood waste in the troughs projected in field conditions.

According to Appendix 1, 482 L/min rain or snow precipitation on 1 km^2 (a_1), or 0.482 mL/min on 1 m^2 (a_2) tailings area must be treated. The maximum flowrate subjected to microbial action in the troughs was 50 mL/min (b) for an average cross section of 10 cm x 15 cm and 240 cm trough length using two troughs (2 x 6.7 L) with a total of 13.4 L wood waste.

A ditch 2 m wide, filled to 1.50 m with wood waste and 50 m long will be assumed for practical purposes. This size is approximately 10 times the cross-section of two troughs side by side and double their lengths (trough size; 10 cm wide, 15 cm deep and 240 cm long; x 10 = 1 m wide, 1.5 m deep and 25 m long) or 4000 times the trough capacity. The cross-section through the wood waste in the ditch is thus 30000 cm^2 or 3 m^2, or 200 times that of the troughs.

If the ditch and its wood waste would be 240 cm long (= combined trough lengths), 200 x 50 mL/min = 10 L/min could be treated. This flow would originate in $\frac{10}{482}$ km^2 or approximately 5 acres according to (a_1). The ditch, however, is 20 times as long so that water from, at least, 20 x 5 acres = 100 acres could be treated with increased flow rate due to extended length disregarding possible maximum physical flowrate limitations. The maximum physical flowrate is approximately also 20 times that preferable for bacterial action (6 $mL/min/cm^2$ = 20 x 0.33 $mL/min/cm^2$) so that the cross-section of wood in the ditch would allow a 200 x 150 x 6 mL/min = 180 L/min flowrate. The validity of "segmentation" in the abating process must still be determined in an experiment using long lengths of wood waste. It refers to the validity of equalizing microbial action at increased flowrate by increasing the distance through the wood waste (p. 38) and eliminating the factor '7' (weekly) used in recirculation.

The same estimate of the abating capacity can be obtained condidering the wood-volume ratio.

A waterflow of 50 mL/min could treat water from $\frac{50}{0.482}$ m^2 = 103.7 m^2 or 0.026 acres according to (a_2). This flow travelled through 13.4 L wood waste. If the ditch contained the same volume ratio of wood waste as the troughs, the water would travel through $\frac{\text{(wood volume) } 13400}{\text{(trough volume) } 10x15x240}$ x ditch volume 150,000 L = 0.372 x 150,000 L = 55,833 L wood waste and treat water from $\frac{55,833}{13.4}$ x 0.026 acres = 108 acres.

The water flowrate in the ditch from yearly precipitation on the average of the above estimates, $\frac{100 + 108}{2}$ = 104 acres or 420877.6 m^2, would be $\frac{(420877.6 \times 10000) \times 25 \text{ (p. 32)}}{(365 \times 24 \times 60) \times 30000 \text{ (p. 36)}}$ mL/min/cm^2 = 6.7 mL/min/cm^2. This is close to the maximum physical flowrate through wood waste (p. 34).

The wood waste fills less than half the trough volume because of the steep trough-position (Fig. 1). If a full volume could be used in a near-level ditch, water from approximately $\frac{1}{0.372}$ x 104 acres = 280 acres (0.372 = wood/trough volume) could be treated. The water flowrate from precipitation on this acreage, however, would be $\frac{280}{104}$ x 6.7 mL/min/cm^2 = 18.0 mL/min/cm^2. This and similar high flowrates exceed the maximum physical flow rate, through wood waste, being 6 mL/min/cm^2.

In order to increase the water treatment capacity, the effective size of the windows must be enlarged. To a certain extents, this can be done by piling gravel against the windows screens, and placing it on the ditch bottom. The size of the windows remains the same to force the waterflow along the same direction. However, it allows a faster waterflow which can be varied with the size of the gravel bed. Using this method, flowrates in trough and ditch lengths can be compared. The maximum flowrate based on the trough diameter would be 10 x 15 x 6 mL/min = 900 mL/min. Approximately the same factor is involved in this water flowrate increase (18), as that in the "segmentation" (20) (p. 36); 50 mL/min x 18 = 900 mL/min and; trough length x 20 = ditch length.

These estimates indicate that the grain size of the wood waste, more than the bacterial action, would be the factor limiting the effluent volume that could be treated. This can be expected from the fact that wood waste is the basis of microbial action.

A wood-waste volume larger than 0.372 (wood volume/trough volume) x ditch volume may primarily increase the (contaminant) storage capacity and reduce wood replacement frequency. The 50-m ditch length is shorter than the water would travel in one day at a maximum flowrate of 6 mL/min/cm^2. One-cm^3 unit contains 0.77 mL water (1 L = 149 g wood waste holds 680 mL water due to porosity and absorbs 60% water; total 680 + (0.6 x 149) mL = 770 mL). A one-cm^3 water unit at this flowrate would require a $\frac{1}{0.77}$ x (24 x 60) x 6 cm = 112 m long ditch to remain one day in contact with the wood. In a 50-m ditch the water would remain for approximately 11 hours in contact with the wood at that rate, or permit water at a 2.7-mL/min/cm^2 flowrate to travel its length in one day. This might be sufficient because of the observation that the pH of water in the troughs increased from 3.5 to 6.95 in 4 hours at 100 mL/min in the troughs (100 mL/min = 0.67 mL/min/cm^2; water at a $\frac{2.7}{0.67}$ = 4 times greater flow rate has a $\frac{24}{4}$ = 6 times longer period to travel). At a 0.33-mL/min/cm^2 rate the water would remain 8 days in contact with 50-m long wood.

The above estimates show merely the feasibility of using a 50-m ditch in an actual process according to the results of the experiments.

In one week recirculation, e.g. at 0.45 mL/min/cm^2 or 68 mL/min, a 1-cm^3 water unit travels 58.9 m through wood waste in the troughs, which is comparable with the ditch length. However, the results of the microbial action may have become superimposed in this recirculation, and the phenomena after a certain period (e.g. $\frac{0.77}{0.45}$ x 240 min = 7 h) may have become the results of recirculation itself on the microbial action. Apart from the rapid pH-increases shortly after introducing fresh solutions, anaerobic conditions (sulphide formation) developed in the three- but not in the one-trough unit (p. 17). This indicates that the water flowrate in the three-trough unit should have been higher to prevent these conditions

from developing. The longer trough length required, therefore, a higher water flowrate. The basic problem to be solved by a field experiment concerns thus the question whether an increase to 6 mL/min/cm^2 flowrate in an increased length of wood waste still allows the microbial action to raise the pH.

APPENIDX 4

Tentative design and size-estimates for an extended trough experiment in the field

The basic material is assumed to be 4 m^3 (2 or 3 truck loads) of tailings placed 15 cm high in a 6-m diameter (28.26 m^2) pond. The maximum water flowrate through the tailings, being approximately 9 times the average yearly precipitation at Elliot Lake, is 6 L/24 h/2565 cm^2 (18). This would produce a flow of 27.5 L/h or 460 mL/min from the pond.

The reservoir should have the capacity of one month effluent to determine the evaporation rate, and have a volume of which the effluent rate can be controlled; e.g. a flow of 27.5 L/h accumulates 19800 L/month requiring a (reservoir) pond 7 m diameter, 1 m high, half filled (≈ 50 cm) with effluent.

If the cross-section of the wood waste in the ditch is 35 cm high and 30 cm wide (1050 cm^2 or 0.1 m^2 in different shapes in the experiments), a continuous water supply from the reservoir would have a maximum $\frac{460}{1050}$ = 0.438 mL/min/cm^2 flowrate. This would be maximum due to tailings porosity and approximately the optimum 60 to 68 mL/min or 0.40 to 0.45 mL/min/cm^2 for bacterial action in the troughs (2.4 m length).

If the volume can be controlled at the 50-cm level of the reservoir, the evaporation rate can be determined by measuring the input required to maintain this level. This would simulate actual evaporation phenomena which occur primarily on the surface and decrease significantly with depth in a tailings (p. 32). The resultant solution, being a mixture of run-off and tailings effluent, only approximates certain conditions. The factor '9' used to increase the average yearly precipitation, actually dilutes the effluent and therefore, decreases its effect (7). Previous observations (19) show that the conductivity of slow-flowing or stagnant water in tailings areas is high compared with that of faster flowing water.

A 25-m long ditch unit consisting of parallel channels having differently shaped cross-sections could be used in the field experiment. This is proportionally longer than a length based on the ratio between the cross-sections of the channel and the ditch in an actual operation (p. 24); 25 m:50 m > 0.1 m^2:3 m^2. Although some general indications about the relationships between flowrates, pH-values, and pH-gradient were obtained

in the experiments using troughs, systematic measurements were not possible due to differences in lag-times, pH-levels, fast pH-increases and other yet-unknown factors. The pH-gradient (or effect of "segmentation") can be measured in comparatively long ditches or troughs. It is possible in the field experiment to increase the water flowrate only after accumulating the water volume in the reservoir. The flowrate through the cross-section of the ditch (3 m^2; p. 25) from drainage through the tailings at 25 $mL/cm^2/a$, resulting from 75% evaporation of 100 mL/cm^2/year precipitation, was 6.5 $mL/min/cm^2$ (100 acres = 404685.6 m^2 and 25 $mL/cm^2/a$). This is the maximum physical flowrate through the wood waste i.e. 5-7 $mL/min/cm^2$ (p. 34). The flowrate through the cross-section of the experimental ditch (0.1 m^2) resulting from a maximum drainage rate of the 28.26-m^2 tailings pond (p. 40), however, was 0.438 $mL/min/cm^2$ and close to the optimum for bacterial action in the troughs. Higher flowrates must, therefore, be produced by an accumulation of the water volume in the reservoir.

It is practically not feasible to reduce the sizes of an actual abatement-system to those of a field experiment, designed to determine the effects of wood-waste length instead of recirculation on the process. The size of the ditch cross-section (3 m^2) is reduced by a factor 30 ($\frac{3}{30}$ m^2 = 0.1 m^2) in the field experiment. The ditch length (50 m) could be reduced by this factor, but a is only halved (50/2m = 25 m) to provide an opportunity to measure pH-gradients. However, a $\frac{100}{30}$ acres = 3.3-acres tailings pond would be required according to the cross-section ratio, which is beyond the economy of the experiment. Water accumulation must, therefore, be used to increase the maximum tailings flowrate of 0.438 $mL/min/cm^2$ due to experiment limitations to the maximum through the wood waste. A water volume stored in one month might be emptied in only two days using a (for wood waste maximum) 6-$mL/min/cm^2$ flowrate. The experiments on the determination of the maximum flowrate should begin by increasing a lower flowrate stepwise to keep the necessity of lengthy fillings of the reservoir to a minimum.

The ditch empties in a 5-m diameter settling pond connected with another 10 m in diameter, both 1 m high.

The evaporation rate must be determined before other experiments can be done. Taking this factor into account, the flowrates can be adjusted by

increasing the (measured) water volume supplied by sprayers in the tailings pond. The flow from the reservoir into the ditch is controlled by a V-notch or ball-valve in the pipe connecting the two units. The water level being higher than the pipe is controlled with a level-measuring instrument (e.g. Soget Inc.) adjusting the water supply. The pH-limit might be set at 3.0. When the pH is lower, the valve is closed. The rise in water level is stopped because the level measuring device turns off the supply. When the pH rises, the valve is opened to allow a waterflow at a specific rate. The water level lowers, activating the level measuring device which opens the water supply. This control is limited at a low flowrate to prevent the formation of stagnant and anaerobic conditions and at a high flowrate to prevent water flowing over the wood. The position of the control-pH-electrode in the ditch must be determined by measuring the pH-gradients at various flowrates because the pH at the reservoir exit will always have the comparatively low value of that of tailings effluents. The flow regulation by the pH-electrode might compensate, therefore, for pH-value variations produced by irregular precipitation and subsequent evaporation and concentration, microbial action, wood-waste channelling and exhaustion, etc. It is also feasible to incorporate a dissolved-oxygen measuring instrument to control the extent of aeration. These controls might promote a state of equilibrium in the system and must be determined in a waterflow through a long wood-waste volume.